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SHOCK SENSITIVITY, A PROPERTY OF MANY ASPECTS

By
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ABSTRACT: (U) Shock sensitivity of an explosive includes its threshold for propagation of steady state detonation at the critical diameter (d_c) as well as its numerous thresholds for initiation of detonation under different transient conditions. Data for TNT charges of differing degrees of homogeneity are used to show a continuous variation of d_c with the initiating pressure P_1 measured with the NOL large scale gap test. An example of a critical curve is constructed in the pressure-time plane; it runs from the threshold conditions at d_c through those at P_1. It is suggested that all other initiating pressures measured for the same charge would also fall on this curve which illustrates the relationship between the different threshold values.

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Shock Sensitivity, A Property of Many Aspects

This work was carried out under task MAT-03L-000/R-011-01-01 IR 59. Its results contribute to the field of explosive detonability and shock sensitivity.

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SHOCK SENSITIVITY, A PROPERTY OF MANY ASPECTS

The "shock sensitivity" of an explosive cannot be described by a single valued parameter. Shock sensitivity encompasses all of the complex reactions of the explosive to many different shock conditions. Such reactions are manifested by the phenomenon of failure diameter for propagation of detonation as well as by the critical initiation pressures for shock to detonation transition observed in the numerous gap, booster, projectile, and wedge experiments. A complete description of an explosive's sensitivity to shock should encompass, therefore, not only the thresholds for initiation under transient conditions but also the threshold for propagation under steady state conditions. Moreover, it should account for the large effect of the physical state of the explosive on both thresholds.

The relationships between these many aspects of shock sensitivity are complex and cannot be simply stated. This situation has led to a general confusion about the meaning of different measurements. It is the purpose of this papar to clarify the situation by describing the relationships between the conditions at the critical diameter and those at the critical initiating pressures (gap test) and then by using measured values for one explosive in a number of different physical states, to demonstrate the trends observed in both critical diameter and critical initiating pressure with increasing charge homogeneity.

TNT was chosen for the present work because it has been so widely studied that more data are available for it than for any other pure explosive. Moreover, it is a castable material and, hence, can provide an almost continuous range of physical heterogeneity between the highly compacted porous charge and the perfect single crystal.

THRESHOLD FOR SHOCK-TO-DETONATION TRANSITION

The critical initiating pressure is defined as the minimum pressure (P_1) required to initiate detonation of the explosive in 50% of the trials. It defines a threshold for the initiation of

detonation under transient conditions. The value of P_i measured in any given test is determined not only by the chemical composition of the test material and its physical state but also, in large part, by the physical dimensions of the test. These dimensions control the times at which rear and lateral rarefactions can arrive at the shock front and relieve the pressure. Thus, each test devised to measure P_i is apt to use a different pressure pulse (pressure-time profile) to excite reaction of the explosive. Different profiles can be obtained by varying the composition and shape of donor explosives in the gap, booster, and wedge tests and by varying projectile material, shape, and velocity in the projectile impact and wedge experiments. They are also obtained by varying the diameter of the acceptor explosive. The explosive response differs as the stimulus differs, and, hence, gives different P_i values in different tests. In other words, not only P_i but also P_i vs time (t) should be specified in each test.

Eleven years ago it was shown theoretically (1) that a limiting pressure-time (P-t) curve exists for a 50% chance of build-up to detonation in homogeneous explosives; the limiting curve divides the impulse plane into a detonation region and a failure region. Brown and Whitbread (2) demonstrated by impact of cylindrical projectiles on two physically heterogeneous explosives that the P_i determined must have a minimum duration for detonation to occur. They also showed qualitatively that, at $P > P_i$ and a duration shorter than that required at the critical pressure level, detonation could also be initiated. Since then there has been rather general agreement that initiation of detonation must be the result of the pressure-time history of the initiating shock, and that a critical limit curve in the P-t plane must exist for each explosive.

In many cases of explosive loading (e.g., a gap test), maximum shock pressure can be determined much more readily than the pressure-time profile. Hence, many of the shock sensitivity measurements have been restricted to pressure measurements only. However, Walker and Wasley (3) have recently combined some plate projectile impact

data (for which pulse duration can be computed from plate thickness) with gap test measurements about which some information on the pressure-time profile was available. These data appear to define a critical ignition energy from which a critical pressure-time limit curve for ignition can be derived. Walker and Wasley also discuss the case of the "sustained" pulse, i.e., one of duration far longer than that required at a given pressure level to effect ignition. They believe that ignition occurs as soon as the critical amount of energy has been transferred to the test explosive from the sustained pulse.

Some of the gap test data used in the above work (3) were obtained with the calibrated NOL large scale gap test (LSGT) (4). Because it will be used for data in this work, its important characteristics will be briefly reviewed. It is a conventional gap test with a 5 cm diam x 5 cm long, 1.51 g/cc tetryl donor and an attenuator gap of polymethyl methacrylate (PMMA) or its equivalent. The acceptor explosive can be tested unconfined or in the moderate confinement of a steel sleeve (3.65 cm ID, 4.76 cm OD). A mild steel witness plate is used in both cases, and the gap length is varied until the 50% value is found, that is, the attenuation at which a hole is punched in the witness plate in 50% of the trials. The system donor/gap has been calibrated (5) to give shock pressure as a function of gap length. This 50% pressure (P_g) at the end of the gap can be converted to the initiating pressure (P_i) transmitted to the explosive by use of the Hugoniot of the gap material (5) and that of the explosive, e.g., cast TNT (6).

The standard donor of the LSGT is approximately point initiated; hence, the detonation front in the donor is spherical and the hydrodynamic flow in the gap and in the acceptor is divergent. The transmitted pressure falls off rapidly. From optical observations of the tetryl/PMMA system, the shock pressure decreases to half its initial amplitude in about one μsec (7). Walker and Wasley (3) estimated that such a pulse was equivalent to a square pulse of an amplitude of 0.9 P_i and 1.6 μsec duration. Although a one-dimensional hydrodynamic flow computation on the tetryl/PMMA system

produced a half-width of 4 μsec (7), analogous two-dimensional computations (8) indicate values of 1.1 to 1.7 μsec, in fair agreement with the original estimate from experimental work.

Like all such tests, the LSGT exhibits a diameter effect. Inasmuch as doubling the length of the standard booster does not affect the measured pressure (9), rear rarefactions play no part in the attenuation. Thus, the observed, as well as the computed, pulse shape can be attributed to the effect of lateral rarefactions on the initial pulse. Because confinement of the charge delays the arrival of lateral rarefactions at the charge axis, we find, for the same measured P_1, that the diameter of the unconfined charge is approximately twice the core diameter of the confined charge, i.e., 76 mm (See Appendix). This value of the equivalant diameter (d_e) seems applicable to a number of different explosives, but the size of the change in measured P_1 with confinement depends on the shock sensitivity of the explosive. The change is greatest for the least sensitive materials (See Appendix).

Both pressed and cast TNT exhibit the usual sensitivity phenomena of shocked solid heterogeneous explosives (10,11): a critical initiating pressure (P_1) for detonation, breakout of detonation downstream from the shocked boundary, and a consistent decrease of both the run distance and delay time to steady-state detonation with increased amplitude of the applied shock. The run distance is the distance from the plane of shock entry into the explosive to the plane in which steady-state detonation is first established. The delay time is the total time from the moment of shock entry to the time at which steady-state detonation begins.

Liquid TNT and presumably single crystal TNT behave as shocked homogeneous explosives (12). They too exhibit a critical initiation pressure, but detonation occurs, after a delay (induction) time, at the plane of shock entry. The detonation wave travels through shocked explosive to overtake the shock wave. There is subsequently a short period of overdrive of the unshocked explosive. The measured induction time decreases with increasing pressure of the initiating shock. It has been shown that a single crystal of RDX can be

initiated to detonation with lower strength shocks than those required for homogeneous initiation (13); liquids can also be initiated at similarly lower pressures, e.g. nitromethane (14) and nitroglycerine (15). These appear to be special cases in which the experimental design is such that the materials' homogeneity can be destroyed before initiation or interaction of the initial shock with the boundary material is required for initiation. Such special cases will not be considered further.

LSGT shock sensitivity values for pressed TNT have been reported in previous work (16) as P_g vs percent theoretical maximum density (% TMD). The trend was the usual one of increasing P_g with increasing compaction. The average particle size of the TNT used for that work was about 150 μ with a maximum particle size of 600 μ. To determine the effect of the initial particle size on the measured P_g, a special batch of TNT was prepared by air cooling a sprayed melt. It too had a weight mean particle size of 150 μ by sieve analysis. It was separated into two fractions: that passing and that retained on a 100 mesh screen (149 μ opening). When these materials of mean particle sizes of 100 and 200 μ, respectively, were compacted isostatically to 80% TMD and tested in the standard confinement of the LSGT the P_g values were 13.0 and 12.6 kbar respectively as compared to 12.8 kbar from the smoothed curve of the earlier work. Although these differences are in the direction expected from test results on other explosives, they are too small to be significant and we conclude that there is no particle size effect evident in this range for P_g measured on pressed TNT in the LSGT.

We have measured a particle size effect on LSGT values for the much less shock sensitive explosive, nitroguanidine (17). In that case the effect was small; it was larger at lower % TMD and disappeared at high compactions. The coarser material showed a slightly greater shock sensitivity. (TNT was tested at 80% TMD to take advantage of the greater effect of particle size on P_g at lower compactions.) In gap tests of smaller effective diameter than the LSGT, the trends found for an insensitive explosive

(nitroguanidine) have been confirmed with more sensitive materials, e.g., tetryl and PETN (18).

The LSGT measurements on TNT have been collected in Table 1. P_g values have been converted to P_1 values by using the Hugoniots of PMMA (5) and of cast TNT (6) except for the one low density charge. In that case an interpolation was made between the Hugoniot for TNT (ρ_o = 1 g/cc) (19) and that at higher density (6). P_1 values at $d_e \geq 3\ d_c$ (the critical diameter) and, hence approximating the infinite diameter value are given for each charge. A single TNT crystal has not been tested, but liquid TNT has been (12) and supplies the limiting value of 125 kbar. [It was assumed that the test was comparable to that on nitromethane (12), i.e., run at a diameter of about 8 inches. Since d_c of TNT (ℓ) at 81 - 85°C is reported as 62 mm (20) and 68 mm (21), $(d_e/d_c) \sim 3$.] The initiating pressure measured for TNT (ℓ) is a limiting value for the crystal because, from the Hugoniots of the solid (6) and of the liquid TNT (22), there is an energy jump across a 125 kbar shock of 250 and 360 cal/g, respectively. If the same fraction of this energy is converted to heat in both cases, the temperature of the shocked solid will be much lower than that of the shocked liquid because c_v (solid) > c_v (liquid) (22). Consequently if 125 kbar is required for homogeneous initiation of the liquid, a higher pressure would be required to initiate the solid. The validity of this conclusion is also supported by a recent calculation of P_1 for a single TNT crystal. Using a measured adiabatic explosion time, Arrhenius kinetics, and an assumed equation of state for the solid, Voskoboynikov et al (23) computed a critical initiating pressure of 200 kbar for the perfectly homogeneous solid TNT.

Values for the two cold pressed charges of Table 1 are smoothed values from previous work (16). The values for the confined charges of two of the castings have been deduced from measurements on bare charges, as described in the Appendix. All values have been arranged in order of increasing physical homogeneity of the charge, judged from a knowledge of its method of preparation. Thus, a rapid cooling and solidification of TNT results in a casting containing many small

TABLE 1

LSGT Shock Sensitivity Data for Various Forms of TNT

Form of Charges	ρ_o g/cc	%TMD	Unconfined (d = 3.81 cm) 50% Point Gap (mm)	P_g (kbar)	P_i (kbar)	Confined (d_e ~ 7.6 cm) 50% Point Gap (mm)	P_g (kbar)	P_i (kbar)	$\frac{d_e}{d_c}$
Pressed at 25°C	1.18	71.5	(50.3	18	13)[b]	63.7	11	8	10
	1.62	98.0	(29.7	43	49)[b]	45.2	22	25	35
Castings									
Poured — Cooling Rate									
1 Clear — Rapid	1.57	95.0	24.9	50	61	(40.2	28	32)[b]	5
2 Creamed — Moderate	1.615	97.75	18.5	62	74	34.3	37	43	3
3[a] Clear — Moderate	1.62	98.0	9.7[c]	87.5[c]	104[c]	(20.6	58	69)[b]	3
4 Clear — Very slow	1.61	97.5	Subcritical[d]			>0[e]			
Perfect Single Crystal	1.65	100	-			-		>125[f]	3

a. Vacuum cast. b. Values in parentheses were not measured. See Appendix. c. Tested at d = 5.08 cm because d_c = 3.81 cm. d. Entering shock at zero gap induced fading reaction. Front travelled at 6.8 mm/μsec for 5 to 6 cm, and then at 4.7 mm/μsec for next 9 to 10 cm. e. Only one shot at zero gap; measured detonation velocity was 6.9 mm/μsec. f. Estimate - see text.

crystals; it should be the most heterogeneous of the castings although more homogeneous than any pressed charge. A vacuum casting should be more homogeneous than a creamed casting both because of the evacuation of any trapped air and because cooling under vacuum would be somewhat slower than the air cooling of the creamed casting. Casting No. 4 was obtained with a heated mold and steam fingers which supplied some heat to the interior of the casting throughout the solidification process. These charges contained three thin metal wires (one along the axis, the others parallel to it with a separation of 3 mm) which served to conduct the heat. The charges so prepared contained a number of large TNT crystals and most closely approximated the case of the single crystal.

Although a single operator might learn to reproduce any of these castings fairly well, the variation from operator to operator and from day to day can be large despite written schedules and procedures. For example, eight different preparations of creamed cast TNT showed a variation of 26.7 to 46.4 kbar in P_g. If the two extreme values are discarded, six charges showed P_g values of 33 to 40 kbar. In view of the sensitivity of P_g to small changes in mold temperature and cooling rate, this range is probably as small as could be expected. The two values measured for Casting 2 of Table 1 (confined and unconfined) were obtained from charges made from the same lot of TNT, and the P_g measured under confinement is the same as the mean value obtained for either the group of eight or that of six creamed cast charges.

The data of Table 1 show two things very clearly: (1) there is a continuous variation in P_i values from the most to the least heterogeneous charge, and (2) the required initiating pressure increases monotonically with increasing physical homogeneity of the charge. Although a smooth trend in the range of cold pressed charges is commonly found, earlier work (16) suggested a discontinuity between the initiating pressure required for the highest density pressed charge and that for a single crystal (RDX or PETN). If the values for the cast charges were omitted from Table 1, a similar apparent jump in P_i would occur for TNT. A castable material can be handled to produce charges of homogeneity bridging the difference between that of

the highest density pressed charge and of the perfect crystal. A comparable treatment for non-castable explosives such as RDX would be the use of a solvent, i.e., solution in place of melting. In both cases, a continuous variation in homogeneity and hence in P_i can probably be obtained.

Finally it should be noted that ρ_o or % TMD which, together with the particle size of the explosive, seems an important variable in determining P_i for pressed charges, has little effect on P_i in the range of the castings. The controlling variable for the entire range, as mentioned above, is the degree of physical homogeneity of the charge. Unfortunately, there is as yet no quantitative measure of this charge characteristic; however, for a chemically homogeneous compound such as TNT, degree of homogeneity would certainly encompass the bulk density (ρ_o) with an appropriate weighting for its greater apparent influence on the behavior of the more heterogeneous charges. Qualitatively it is clear that the shock sensitivity, as measured by P_i, decreases montonically with increasing physical homogeneity.

THRESHOLD FOR PROPAGATION OF DETONATION

The failure or critical diameter (d_c) determines the charge size at which there exists a threshold for the propagation of detonation under steady state conditions. By definition, d_c is that diameter of a cylindrical charge at or above which detonation propagates and below which it fails. The existence of a failure diameter is the result of two dimensional effects. In accord with this and with the shock-to-detonation transitions discussed in the previous section, d_c defines that charge size at which the steady-state detonation wave has been attenuated from its infinite diameter value by lateral rarefactions until it is just critical for initiation. In other words, at d_c the pressure pulse between the von Neumann shock front and the C-J plane is just critical for initiating detonation after a run length equal to the reaction zone length and a total delay time equal to the reaction time. Thus at d_c, the transient initiation phenomena just fit into the reaction zone at the threshold of steady-state propagation. This is the rather complex relationship between the explosive behavior at

these different thresholds, each of which is a different facet of shock sensitivity. A quantitative illustration of this proposed relationship will be given later.

Available Data on d_c of TNT

In the range of cold pressed charges, the variation of the critical diameter with the charge porosity has served as the basis of a convenient classification of explosives into two groups (16). Group 1, typified by TNT, exhibits decreasing d_c with increasing compaction (increasing % TMD). Group 2, typified by ammonium perchlorate (AP), exhibits the reverse trend. As a result of the different failure behavior, the two groups also exhibit differences in their detonation velocity (D) vs ρ_o curves at finite diameters. Members of Group 1 have linear D vs ρ_o curves whereas those of Group 2 can exhibit D vs ρ_o curves with a maximum in D. In later work (17) we found that the division between the two groups was not as sharp as we first thought, that some materials, e.g., nitroguanidine, have a U shaped d_c vs ρ_o curve and exhibit Group 1 patterns at lower % TMD, Group 2 patterns at higher % TMD. It is probable that any pressed explosive can behave in this way provided the necessary range in degree of compaction can be achieved experimentally.

Most of the d_c measurements on pressed TNT (porous, granular compacts) have been made by Russian investigators. Fig. 1 shows some of these data plotted d_c vs ρ_o. The two solid lines are values reported by Bobolev (24) for fine and coarse TNT. These curves show the Group 1 behavior described above and also demonstrate the effect of particle size on critical diameter. In the ρ_o range of 0.85 to 1.23 g/cc, d_c is decreased by a factor of 2 to 3 for a decrease in the initial average particle diameter (increase in surface area) of about a factor of 4. It should be noted, however, that the curve for the fine TNT ends at 75%, probably because of pressing difficulties. If experimental data could be obtained to extend that curve, it should approach the curve for the initially coarser TNT even as the two P_i vs ρ_o curves become coincident at high compactions. That this is probably the case is indicated by a recent determination (25) on fine

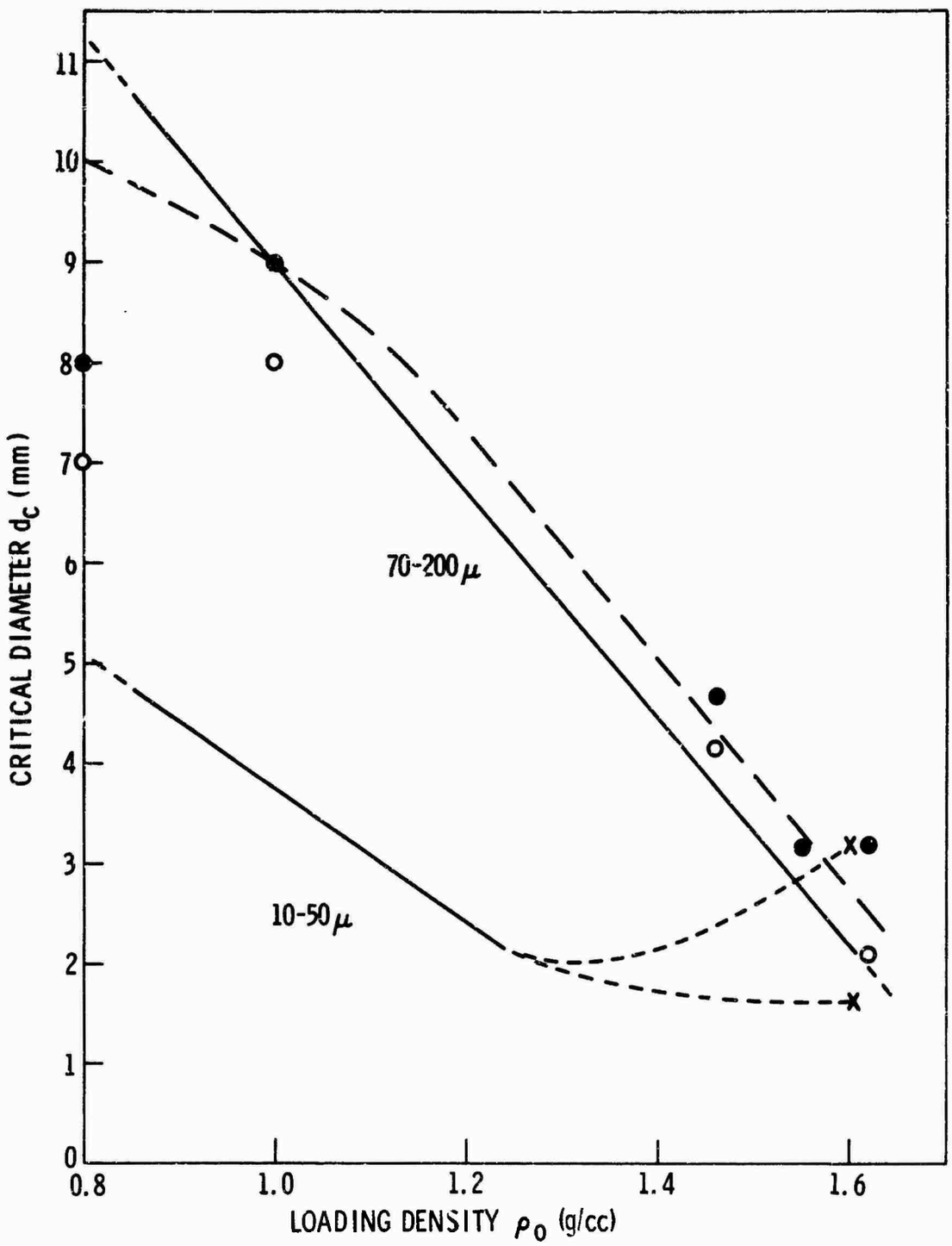

FIG. 1 FAILURE LIMIT CURVES FOR TNT IN DIAMETER - DENSITY PLANE
(——— REF 24; x REF 25; ● DETONATION ○ FAILURE, REF 28;
— — CURVE CHOSEN FOR REF 28 DATA; – – – – – INTERPOLATION)

(20 - 70$_u$) TNT at 97% TMD. In this work a critical slab thickness (h) was measured; it and the approximate $d_c \simeq 2h$ are plotted as crosses in Figure 1. Either value indicates that the fine TNT critical curve will approach or go through a minimum and that at high compaction there will be no significant difference in d_c of the initially fine and initially coarse TNT.

Although there is only one set of data for the fine TNT, there are several for the coarser material. Dremin et al (26) quote limit data from Apin and Stesik (27) for 100 $_u$ TNT. That failure limit curve, not shown in Figure 1, lies 0.8 to 0.2mm below Bobolev's curve for 70 - 200$_u$ TNT, about where it should be for a small decrease in the average particle size. The most recent data are those of Stesik and Akimova (28); their limiting shots for failure and detonation are plotted in Figure 1. Over the range 1.0 to 1.62 g/cc they agree quite well with the data of reference 24; at 0.8 g/cc there is a large disagreement. The close agreement at higher densities makes the size of the discrepancy between the most porous charges seem improbable. Examination of the D vs reciprocal diameter (d^{-1}) curve (28) for the charges at ρ_o = 0.8 g/cc shows a sharp change in slope at d = 10mm. For this reason, d_c (0.8 g/cc) = 10mm is used here instead of the lower value selected in reference 28. (At d < d_c, it is often difficult to distinguish an overdriven shock from a steady-state detonation in a low density charge of moderate length.) With this change, the reference 28 data are in far better agreement with data from both reference 27 and reference 24, as shown in Figure 1.

The possible forms of the lower curve of Figure 1 at higher density strongly suggests that TNT can be put in a physical state in which it will exhibit a U shaped d_c vs ρ_o curve. This possibility has been recently confirmed with measurements on hot pressed (72° - 76°C) TNT. In the narrow range of 1.60 to 1.65 g/cc in ρ_o and 8 to 13mm in d, these charges exhibit Group 2 patterns for both D vs ρ_o and d_c vs ρ_o curves (29) i.e., a maximum D in the D vs ρ_o curve and d_c increasing with increasing ρ_o. The data are plotted in Figure 2.

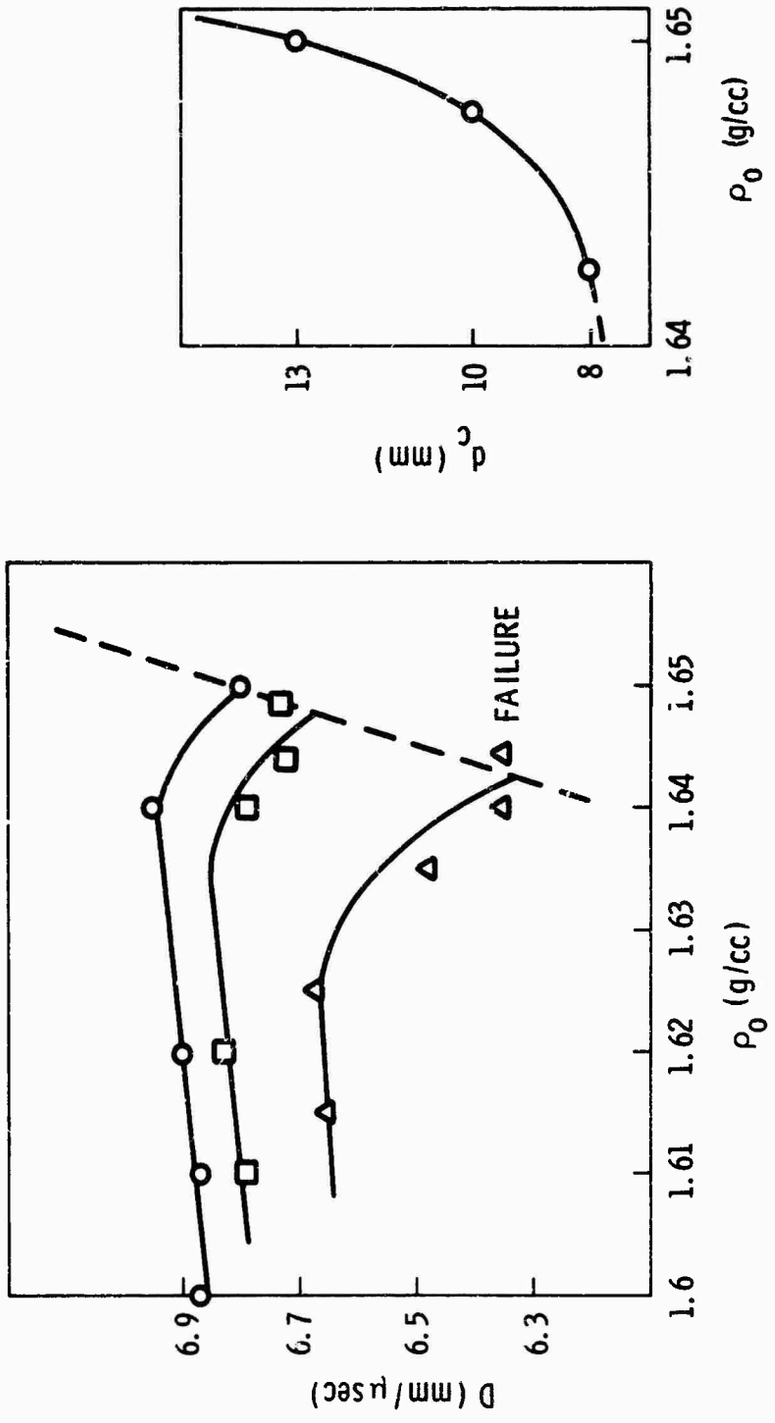

FIG. 2 DATA (REF 29) SHOWING BEHAVIOR OF HOT PRESSED TNT CHARGES

The above measurements on pressed charges are summarized in Table 2 which also includes available data for cast TNT. The data have been arranged in order of increasing physical homogeneity of the charge, as were those of Table 1. As in the case of P_i, there is a continuous variation in d_c from the most to the least heterogeneous charge. The gap between the values for the highest density pressed charge and the single crystal (with d_c greater than that of Casting 4) is smoothly bridged by charges produced by the different methods of preparation. Similarly, the gap between the cold pressings (heterogeneous and permeable to fluids) and the castings (approximately homogeneous and impermeable) can be bridged by hot pressing. Pure TNT melts at 81°C; hence, pressing at 72 - 76°C will cause some local melting and flow so that the charges contain both permeable and impermeable regions. In the region of cold pressed charges, d_c decreases with increasing degree of homogeneity (a Group 1 pattern), but this trend is reversed in the region of hot pressing. Thereafter, d_c, like P_i, increases with increasing homogeneity. The overall trend strongly suggests that permeability, permitting convective heat transfer by flow of hot gas products, has a role in the initiation and propagation of detonation. Finally the data of Table 2 show that the effect of the initial particle size on d_c is appreciable at low % TMD and negligible at high % TMD, as it was for P_i.

Other Information about Critical Conditions

More information can be obtained about the failure conditions if other measurements are made in addition to d_c. In particular, from the detonation velocity at d_c (D_c), an estimate of the detonation pressure at critical conditions is

$$P_{jc} \cong \rho_o \, D_c^2/4 \qquad (1)$$

A measure of the reaction zone length (x) leads to an estimate of reaction time (τ). Since $x = (D - \bar{u})\tau$ where $\bar{u}$ is the average particle velocity in the reaction zone, the estimate $\bar{u} = 1.2\, u_j$ leads to $x_i = f(\gamma)\, D_i \tau_i$ where $f(\gamma)$ is a slowly varying function of the adiabatic exponent gamma; $f(\gamma)$ can be approximated, as in reference (33), by 2/3 to give

TABLE 2

Critical Diameters of Various Forms of TNT

Form of Charges	ρ_o g/cc	%TMD	d_c mm	Reference
Pressed at 25°C				
ca. 140 μ	1.18	71.5	7.5, 6.4, 7.0	24,27,28
	1.62	98.0	2.0, 1.8, 2.5	24,27,28
ca. 30 μ	1.18	71.5	2.5	24
	1.60	97.0	ca. 2.5	25
Pressed at 72 - 76°C	1.64	99.2	7.8	29
Castings				
Poured / Cooling Rate				
1 Clear / Rapid	1.62	98.0	14	28
2 Creamed / Moderate	1.61	97.5	24,27	30,31
3a Clear / Moderate	1.62	98.0	38	32
4 Clear / Very slow	1.61	97.5	>38	32
Perfect Single Crystal	1.65	100		

a. Vacuum cast.

$$\tau_i = 1.5\ x_i/D_i \qquad (2)$$

Equation (2) gives the approximate value for the ideal or infinite diameter detonation reaction time because measurements or estimates of x are made at conditions approaching ideal. For near voidless materials, however, $D_c \cong D_i$ and τ_i should be a good approximation for τ_c. Finally an estimate of the energy required for propagation at d_c can be obtained from

$$E\ (cal/cm^2) = P^2 \tau/\rho_o\ U \qquad (3)$$

Where U is the shock velocity of amplitude P in the unreacting explosive. Walker and Wasley (3) derived Equation (3) for a square pressure pulse of amplitude P and duration τ created by high velocity impact of an explosive projectile against an explosive target.

If P, τ, ρ_o, and U are in units of kbar, μsec, g/cm³, and mm/μsec, respectively, the conversion factor is 0.239. With the hydrodynamic relation, $P = \rho_o U u$, Equation (3) can be converted to

$$E = P\tau u \qquad (4)$$

Where u is particle velocity. For the units of kbar, μsec and mm/μsec, a factor of 2.39 gives E in cal/cm². To obtain the energy value at d_c, where $U = D_c$, we approximate $P \simeq P_{jc}$ and $\tau_c = \tau_i$. The result is a low estimate because the square pressure pulse equivalent to the pulse between the von Neumann and C-J planes should have an amplitude greater than P_{jc} (τ_i is probably less than τ_c as well).

Stesik and Akimova (28) reported, in addition to the d_c values already used, a number of D vs d measurements and also derived reaction zone length data. Their data and results computed from them with Equations (1) to (4) are summarized in Table 3. All the critical parameters of the pressed charges show a smooth variation with ρ_o or % TMD, but the only linear curves are d_c vs % TMD and log P_{jc} vs % TMD. The rest are, like (D_c/D_i) vs % TMD, concave upward. The tabulated values of (D_c/D_i) show the low values (ca. 0.6) typical of loose powder charges and the high values (ca. 0.95) typical of cast or pressed charges at 95% or more of their voidless density (see Figure 3). The detonation pressure at the failure limit is,

TABLE 3

Additional Data for TNT in Several Different Forms

ρ_o g/cc	%TMD	Parameters at Failure Conditions					Ideal Reaction Zone			Energy at d_c
		d_c mm a	D_c mm/µsec a	P_{jc} kbar Eq.1	$\frac{D_c}{D_i}$ a	$\frac{P_c}{P_i}$ Eq.1	x mm b	τ µsec Eq.2	t µsec a	E cal/cm^2 Eq.3
					Pressed Charges					
0.80	48.5	10[c]	2.80[c]	16	0.64[c]	0.44	4.0	1.4	0.56	38
1.00	60.6	9.0	3.44	30	0.69	0.48	2.4	0.72	0.40	44
1.46	88.5	4.3	5.77	121	0.88	0.74	0.30	0.069	0.095	28
1.55	94.0	3.3	6.34	156	0.93	0.86	0.23	0.050	0.051	29
1.62	98.2	2.5	6.63	178	0.95	0.90	0.21	0.045	0.034	32
					Cast Charge (rapidly cooled)					
1.62	98.2	15.0	6.61	177	0.94	0.88	0.9	0.19	0.15	133

a. Ref. (28).
b. From $x = d(1 - D/D_i)$, Ref. (34). See Ref. (35) for these specific values.
c. Changed from Ref. (28) values as shown in Fig. 1.

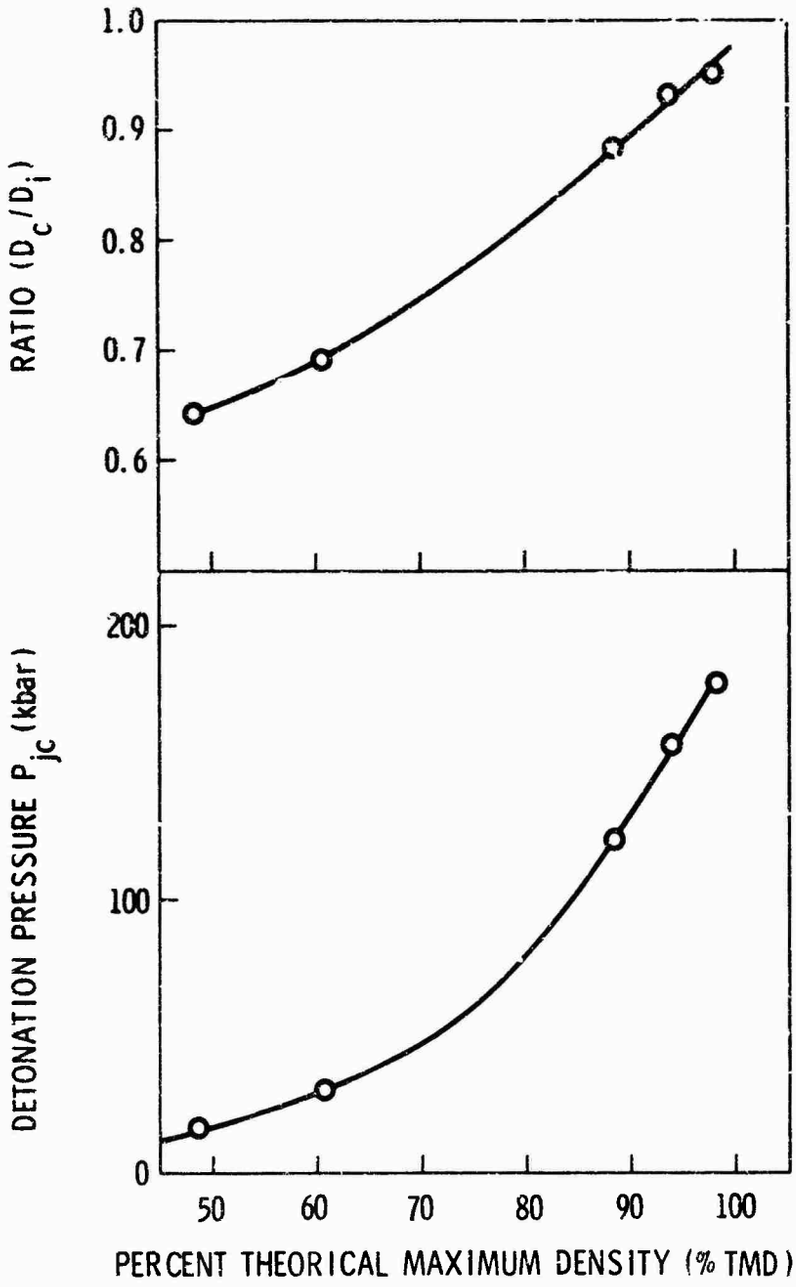

FIG. 3 DETONATION VELOCITY AND PRESSURE ALONG FAILURE CURVE FOR PRESSED TNT (ca. 150μ)

of course, a smaller fraction of the corresponding infinite diameter value than is D_c because, by the approximation of Equation (1), $P_{jc}/P_{ji} \cong (D_c/D_i)^2$.

There is at present some confusion about measuring detonation reaction zone length and reaction time. Table 3 gives reaction zone lengths (x_i) and reaction time (τ_i) computed from Eyring's curved front theory. Stesik and Akimova (28) obtained an experimental value of the zone length on the basis of calibrating their system with one series of free surface velocity measurements on explosively driven plates of different thicknesses. They also computed from these results a detonation reaction time (t_i) which is presented for comparison in Table 3. The times τ were chosen for the present treatment because they produce a linear curve, log τ vs % TMD, which is also a fairly good approximation to the reference 28 data. Both τ and t are of the same order of magnitude as the more recently reported direct measurements of reaction time (36). The reference 36 data lie between the τ and t values of Table 3 at ρ_o = 0.8 to 1.0 g/cc and above them at 1.4 g/cc, as Figure 4 shows. No comparison is made for results on cast TNT since there is no way to be sure that the castings of references 28 and 36 are comparable.

The last column of Table 3 contains the values of energy per unit area (E) delivered to the explosive to sustain propagation at the critical conditions. In view of the approximations used, E might be constant over the range of the pressed charges but it is certainly lower than the value required for a cast charge. It should be noted that if Equation (3) is converted to energy per gram instead of energy per unit area, it is equal to u_{jc}^3 and shows a smooth variation with % TMD as do the other detonation parameters at $d = d_c$.

Finally the data of Table 3 can be used to construct a limit curve in the pressure-time plane for pressed TNT charges. This is shown in Figure 5 where the curve divides the plane into a super- and a subcritical region.

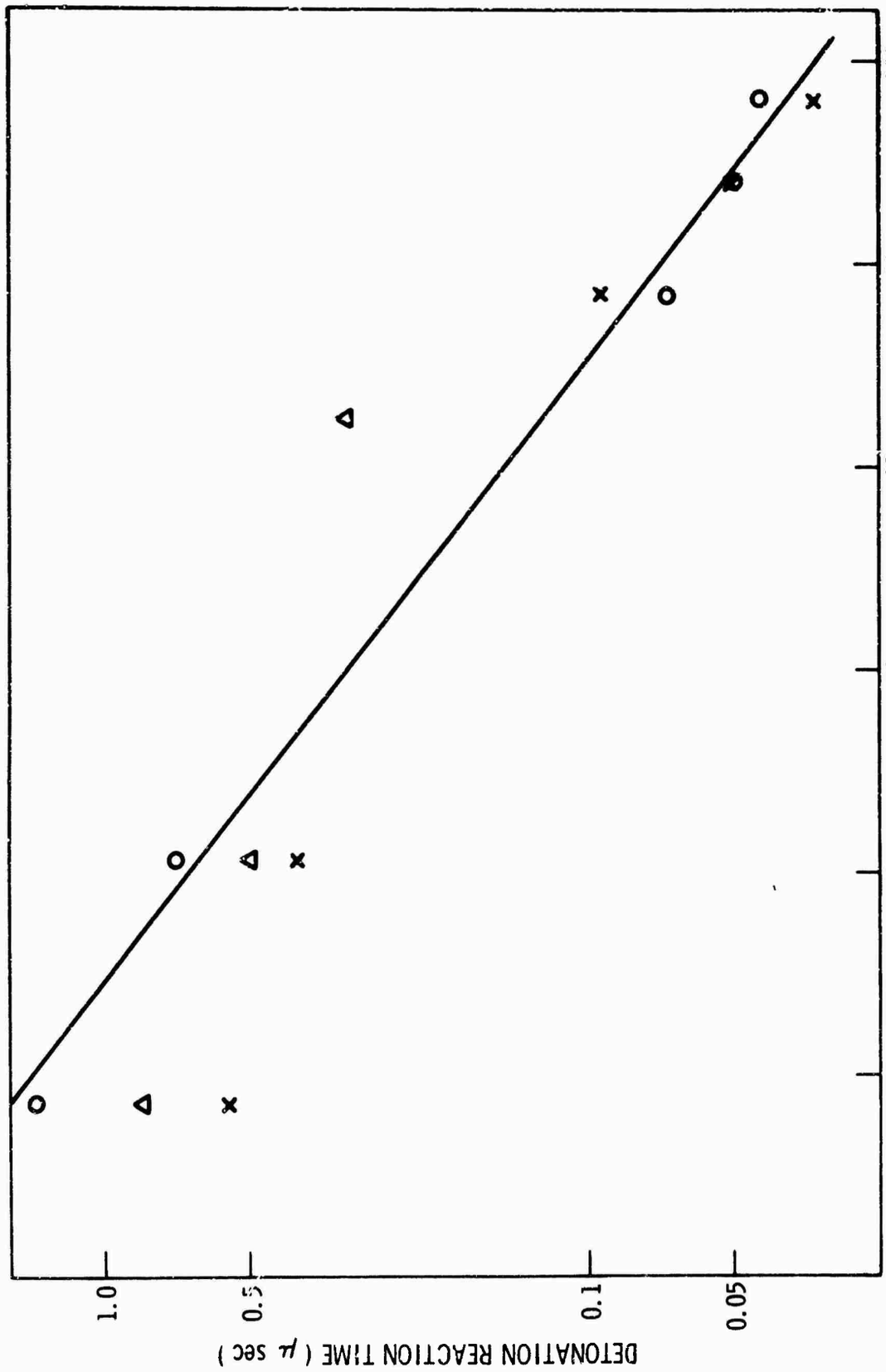

FIG. 4 COMPARISON OF TNT REACTION TIMES [○ τ, TABLE 3 ; × t, TABLE 3 ; △ REF 36]

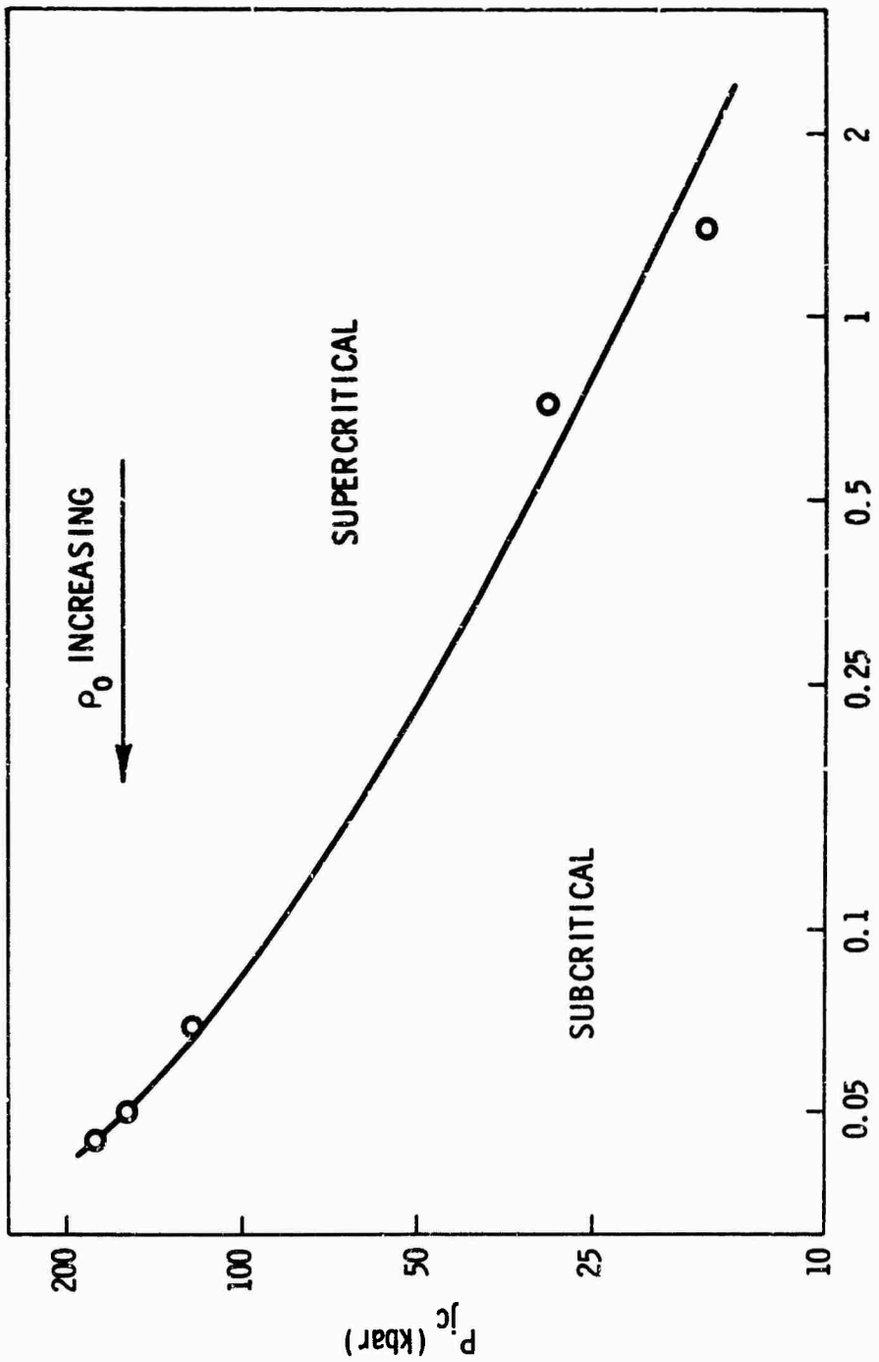

FIG. 5 CRITICAL CURVE FOR PROPAGATION IN PRESSURE-TIME PLANE FOR PRESSED TNT CHARGES

DISCUSSION

The data gathered for TNT have shown that both the critical initiating pressure P_i and the critical diameter d_c are determined in large part by the degree of physical homogeneity of the charge. It is to be expected, therefore, that these two threshold values will be related to each other, and the plot of d_c vs P_i shown in Figure 6 affirms such a relationship by showing a smooth curve over the entire experimental range. This curve also serves as a graphic summary of much of our present information on the critical behavior of an organic explosive.

Although there is no quantitative measure of the degree of physical homogeneity, we know that it varies from very low at the extreme left of Figure 6 (high porosity, cold pressed charges) to very high at the extreme right (100% when the extrapolated curve reaches the perfect single crystal). These extremes are indicated on the figure. Between these extremes, P_i shows a monotonic increase with increasing homogeneity and no particle size effect in the range of cold pressed charges. (That is, none can be detected down to 80% TMD in the LSGT. Other tests do show a small effect for other explosives.) At the extreme right (single crystal) ignition and initiation must be by a homogeneous mechanism since no other is available. At the extreme left, it is generally agreed that initiation must be by a hot spot mechanism, i.e., surface reaction at areas of energy concentration. This heterogeneous mechanism is accepted because the measured initiating pressure is far too low to effect by shock compression a significant temperature rise throughout the bulk of the material. As the charges are changed from heterogeneous to homogeneous, the ignition mechanism also changes; it follows that, in some intermediate region, initiation must be by both heterogeneous and homogeneous mechanisms acting simultaneously. The effect of degree of homogeneity on P_i is attributed to its reflection of the concentration, distribution, and size of hot spot sites.

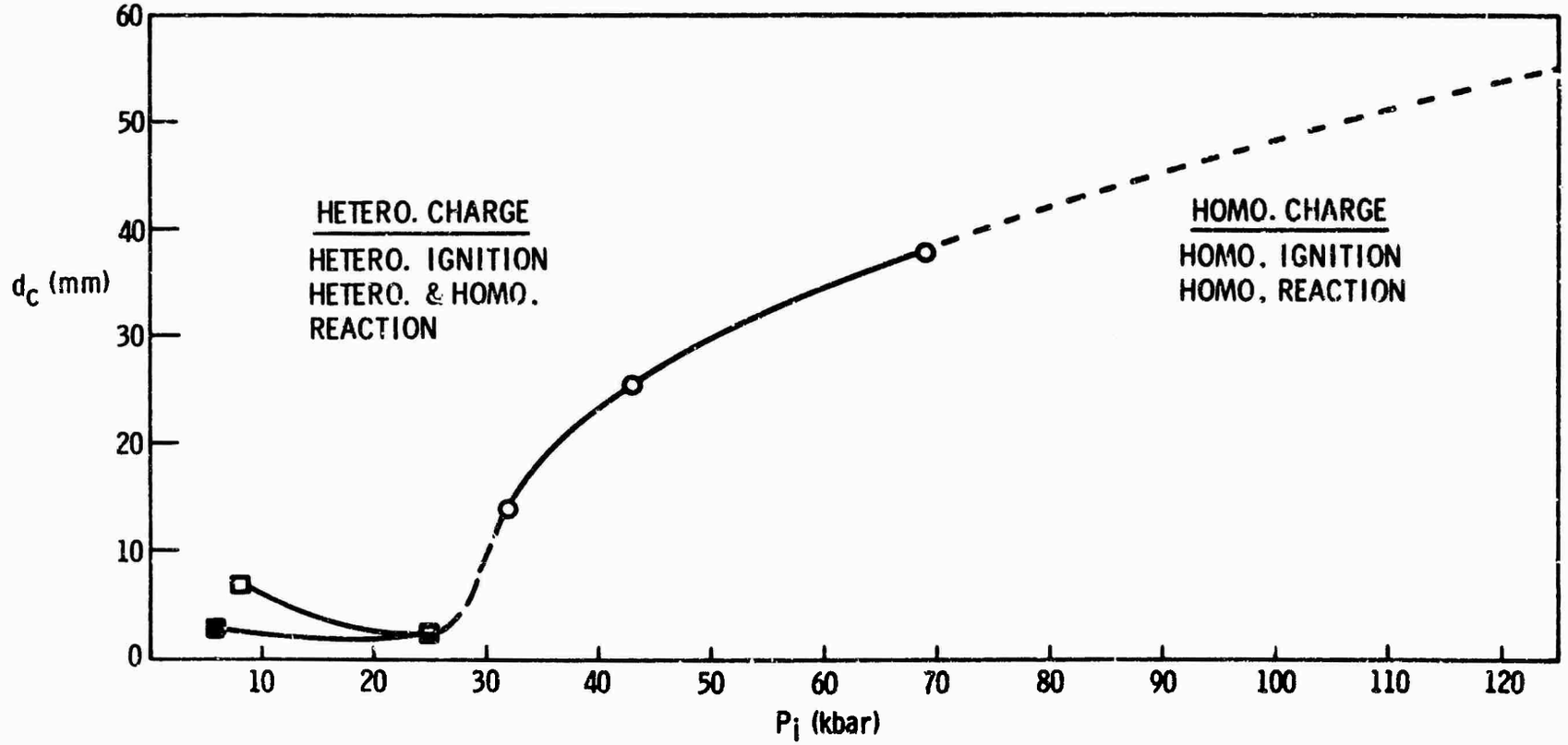

FIG. 6 VARIATION OF CRITICAL DIAMETER WITH CRITICAL INITIATING PRESSURE FOR SEVERAL FORMS OF TNT
(COLD PRESSED CHARGES: □ COARSE, ■ FINE;
HOT PRESSED CHARGES — —; CAST CHARGES O ; EXTRAPOLATION - - -)

In the region of cold pressed charges, a particle size effect on d_c has been indicated. The Group 1 behavior of decreasing d_c with increasing % TMD, shown by the coarse TNT, was previously attributed to increasing domination of the heterogeneous reaction by the homogeneous (16). Thus, at higher density and higher reaction pressure, the dominance of bulk over surface reaction could result in shorter reaction times and reaction zone lengths which, in turn, would result in lower d_c values. This still seems a reasonable suggestion because detonation pressures of 120-180 kbar (Table 3 and Fig. 5) are quite high enough to cause appreciable bulk heating during shock compression. But the apparent reversal in trend shown by the fine TNT and the obvious reversal in trend (d_c vs P_i or d_c vs degree of homogeneity) in the hot pressed charge range, as compared to the cold-pressed, suggests that another factor should be considered. Because the behavior of the hot pressed charges bridges that of the cold-pressed and cast which are, respectively, permeable and impermeable, the new factor might well be the flow of detonation products through the charge. If so, convective heat transfer from such flow must play a role such that initiation is easier to achieve when the flow is optimum in permeable charges. Charges made of initially coarse explosive are more permeable than those made of fine (at the same % TMD) until the compaction eliminates any difference. Hence it may well be a difference in permeability rather than in total surface area that is responsible for the particle size effect found in the cold-pressed TNT charges.

This suggestion is strengthened by the apparent importance of permeability in the transition from burning to detonation in granular compacts (37). Although permeability was not the only factor affecting the ease of transition (for example, surface to volume ratio of the individual particles and energy produced by chemical reaction were also considered), Griffiths and Groocock (37) found it a very important one. They proposed that the high velocity combustion necessary for transition was possible because of a convective transfer of energy from hot reaction gases to solid unreacted particles. Moreover, their curve of the length of burning before detonation vs permeability of HMX charges pressed to different densities was very similar to the

curves they obtained by pressing to a constant density and varying the permeability by varying the initial particle size. A shock-to-detonation transition is a very rapid burning-to-detonation transition in which experimental time resolution is difficult. Mechanisms operative in more easily resolved transitions(37) may also be operative here.

In this connection it should be noted that the phenomenon of "overshoot" observed in the shock initiation of detonation in cold pressed charges (10, 38, 39) is not observed in hot pressed charges (40) or in cast charges (10). The extent of overshoot in cold pressed charges is greatest for the most porous and least for the most compact (10). By arguments similar to those already used, permeability of the charge may be responsible for the appearance of overshoot.

The details of exactly how a forced convective flow contributes to the shock-to-detonation transition have not yet been determined. The initial flow would be expected to be slower than the supersonic progress of the initial shock front. Hence any reaction it induced would occur after the passage of the shock although subsequent growth of that reaction could result in producing a front which could overtake the shock. This sequence of events could be responsible for the observed decrease of pressure in the acceptor with the length of the shock path into the explosive. The initial decrease of pressure is followed by an increase (at greater path lengths) when a successful transition to detonation occurs (41).

Figure 6 summarizes the large effects of the physical homogeneity on the propagation and initiation thresholds of a pure, chemically homogeneous explosive. Also indicated are the suggested mechanisms associated with the different ranges. The complexity of Fig. 6 illustrates the impossibility of creating a single satisfactory model for a theoretical treatment of either failure or shock-to-detonation transition over the entire range of variation in initial physical state. At the same time, however, Fig. 6 shows that there are no discontinuous changes in the threshold values when the preparation can be varied to give charges of different degrees of homogeneity so that

they bridge the rather large gap between the highest density pressed charge and the perfect single crystal.

Although Fig. 6 demonstrates the continuum of threshold values, it does not provide a quantitative example of the relationship between conditions at these two types of threshold i.e., of the transient initiation phenomena occurring within the steady state reaction zone at the threshold of propagation. We can do this in two ways: (a) plot the two sets of pressure-time data (those at d_c and those from the LSGT) on a log-log scale, as suggested by Fig. 5, and approximate the limit curve by a straight line or (b) use the concept of a critical energy for initiation of detonation, compute that energy from the measurements at d_c with Eq. (3) and use it in Eq. (4) to define the limit curve. In either case, we must know the Hugoniot (P vs u) of the non-reacting explosive or approximate it in some way. There are several Hugoniots for high density TNT which can be used for the near voidless TNT, pressed or cast, but there is only one for a very porous (1.0 g/cc) TNT (19). There is some question about the possibility of shocking such a porous material without inducing reaction, i.e., the Hugoniot data may be those of a partially reacting material rather than the desired data for the non-reacting material. Moreover, this very porous charge is in the region where the effect of the initial particle size is greatest (see Fig. 6) and where we lack the necessary critical data on charges prepared from fine TNT. For both of these reasons, we chose to use pressed TNT of ρ_o = 1.62 g/cc.

Table 3 shows that the "critical energy" for initiation of the high density compact is 32 cal/cm^2. This is remarkably and probably fortuitously close to the energy limit of 33 cal/cm^2 Walker and Wasley report for ignition of pressed TNT at 1.64 g/cc. Our value is low because of approximating the critical pressure pulse with a square one of amplitude P_{jc} (a minimum rather than average value) but it does seem to be of the right order of magnitude. It is combined with the Hugoniot data (6) in Eq. (4) to generate the limit curve of Fig. 7. The curve is slightly concave upward, but can be fairly well approximated by a straight line. Moreover the estimated square pulse

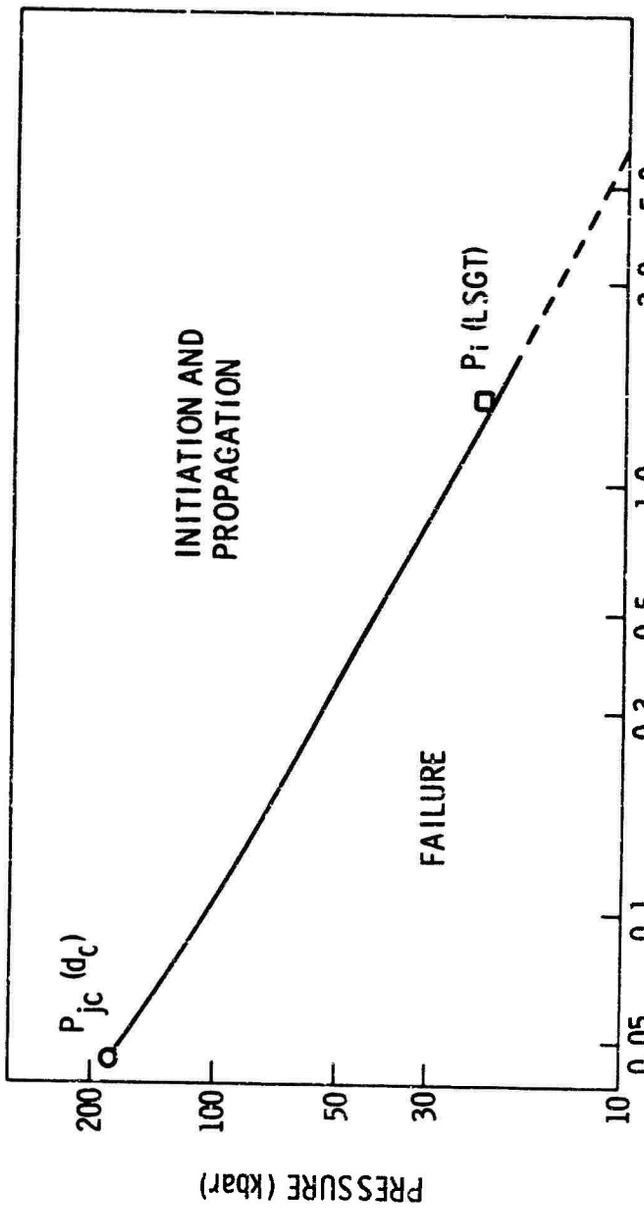

FIG. 7 CRITICAL CURVE THROUGH THRESHOLD VALUES FOR PRESSED TNT (ρ_0 = 1.62, E = 32 cal/cm^2)

equivalent of the intitiating pulse used in the LSGT (0.9 P_i, 1.6 μsec) falls on the limit curve as shown, well within errors to be expected from those introduced experimentally as well as by the approximations used. The limit curve divides the P-t plane into a possible initiation and a failure region (above and below the curve, respectively). The curve originates at the P-t conditions found at the critical diameter threshold and runs through the continuum of (P,t) values which includes all the threshold values for initiation measured in the various gap, wedge, projectile, and booster tests. The conditions for the large scale gap test fall on the curve toward its lower end; the curve probably terminates shortly beyond that point since there is probably an upper time limit in which the critical energy must be delivered in order to initiate detonation. This particular example provides, therefore, a consistent and satisfying illustration of the conceptual relationship between conditions at the threshold for propagation and the numerous thresholds for initiation. It also supports the concept of a critical energy of initiation, but further tests with improved data should certainly be made.

In principle, a limit curve analogous to that for the pressed TNT can be constructed for the cast TNT. In fact, energies computed for the cast charge (rapidly cooled) of Table 3 from critical diameter data and from comparable P_i data (Table 1) differ by a factor of about two. This discrepancy is attributed to error in the reaction time used for the cast TNT. If we assume that the highest density pressed charge and all the castings have the same values D_c and P_{jc}, as the Table 3 data suggest, we can estimate critical energies and reaction times from Eq. (3) and the P_i data of Table 1. With the LSGT conditions of $P = 0.9\ P_i$, $t = 1.6$ μsec, Eq. (3) indicates relative reaction times at d_c of 1, 1.6, 2.6, and 5.9, respectively, for the pressed, rapidly cooled cast, creamed cast, and vacuum cast charges. This is a reasonable trend and gives an increase in critical energy from the high density compact to Casting 1 of 1.6 instead of 4.1 times as shown in Table 3.

SUMMARY

The various aspects of shock sensitivity have been illustrated with data obtained for TNT charges of varying degrees of physical homogeneity. Both the critical diameter for the propagation of detonation (d_c) and the critical initiating pressure measured with the LSGT (P_i) show continuous change with charge homogeneity. P_i increases (ease of initiation decreases) monotonically with increasing charge homogeneity. The same trend was observed for d_c in the region of cast charges, but the reverse trend occurs in the region of cold pressed charges. The reversal occurs in the region of hot pressed charges which bridges the cold-pressed, permeable charges and the cast, impermeable ones. The reversal is associated with the effect of permeability on the process of initiating detonation.

It is proposed that any charge will exhibit a critical curve in the pressure-time plane and that such a curve will start at a point corresponding to the detonation pressure and reaction time at d_c. The limit curve will then run through a continuum of (P,t) values corresponding to the various gap, booster, wedge, and projectile test values for sensitivity. In an example for pressed TNT at ρ_o = 1.62 g/cc, P_i from the LSGT fell on such a curve computed from a critical energy of initiation; the energy was evaluated from data obtained at d_c. This example supports the proposed model in which the transient initiation phenomena occur within the reaction zone at the threshold of steady state propagation. It also supports the concept of critical energy for initiation of detonation. Further tests of both concepts should be made with improved data.

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APPENDIX

Equivalent Diameter for NOL LSGT Confinement

In some of the earliest work on quantitative measurement of shock sensitivity (2,42) the charge diameter effect on the critical initiating shock was evident. This raises the question of what bare charge diameter would result in behavior equivalent to that exhibited by the explosive in the regular gap test confinement. We showed some time ago that this confinement on cast Comp B gave a gap pressure predicted for a bare charge of 75 mm diameter (43). The prediction could be made from a linear relationship established between 50% pressure (P_g) and the reciprocal charge diameter. The effective diameter of the confined charge was determined by replacing the confining material with an equal mass of explosive, still in the cylindrical configuration. If this relationship holds for other explosives besides Comp B, the effective diameter d_e would probably have much the same value because the high density steel has much more effect than the lower density explosive in determining d_e.

In recent work, we have found that a fine (ca. 7μ) ammonium perchlorate dead-presses in the gap test at $\rho_o \geq 1.58$ g/cc, i.e., the material becomes subcritical for propagating detonation. Another fine ammonium perchlorate (ca. 10μ) exhibited a critical diameter of 8 mm at $\rho_o = 1.58$ g/cc (44). Again the gap confinement resulted in a sensitivity behavior exhibited by a 75-80 mm unconfined charge.

Cast TNT lies between this pressed charge and cast Comp B in its shock sensitivity behavior. It seems reasonable to assume that d_e of cast TNT in the gap test confinement will be about 76.2 mm (3 inches), and this value has been used in estimating the ratio d_e/d_c of Table 1. Although the regular confinement results in approximately the same d_e for different explosives, the diameter effect on P_g (or P_i) differs markedly with the sensitivity of the explosive. Thus $-(\Delta P_i/\Delta d^{-1})$ is 35, 140, and 240 kbar cm, respectively, for cast DINA, cast Comp B, and creamed cast TNT. The gradient is determined from P_g values measured on confined and unconfined charges (d = 3.81 cm) with

$d_e \sim 76$ mm for the former. (See Table A1).

There are several ways of estimating the initiating pressures to be expected for confined charges of TNT Casting 1 and 3 (See Table 1) from the measured values on the unconfined charges. The simplest is to use the linear relationship between gap thickness for the confined and unconfined charge. This is indicated when the data for cast DINA, Comp B, and TNT of Table A1 are plotted in Fig. A1. It should be mentioned that two pairs of pentolite values (5,43) do not fall on the curve, but the range covered by these two values and six other values from confined samples is indicated. The upper part of this area lies quite close to the curve, and makes it probable that if the pentolite composition (PETN/TNT, 50/50) and casting had been as well controlled as those of Comp B, its data too would fall on the curve. (Many tests were made on pentolite castings because of difficulties encountered in trying to control the slurry viscosity.)

The upper curve of Fig. A1 shows the relation between 50% gap thickness of the unconfined ($d = 3.81$ cm) and confined ($d_e \sim 7.6$ cm) charges. The lower curve is drawn parallel to the upper through a single point in which the unconfined charge had $d = 5.08$ cm. The single point was obtained by extrapolation of the Comp B data of Table A1. (For the three measured values of Table A1, the 50% gap thickness varies linearly with the charge diameter.)

TABLE A-1

Data Showing Effect of Confinement on 50% Gap and P_i

Material[a]	ρ_o g/cc	d_e cm	50% Point Gap in. x 10^2	50% Point P_g kbar	50% Point P_i kbar	Slope[b] $\Delta P/\Delta d^{-1}$ kbar-cm
DINA	1.60	3.81	226	13.6	15.0	
		7.62	279	9.1	10.4	35.1
Comp B	1.70	3.81	143	33.3	41.3	
		4.76	159	27.7	34.0	
		(5.08	164½	26.2	32.2)[c]	
		7.50	201	17.2	20.7	140.4
TNT	1.62	3.81	73	61.8	74.3	
	1.61	7.62	135	36.2	42.8	240.4

a. All material were cast. DINA is diethylnitramine dinitrate and these test results were first reported in Ref. (5). (The casting of DINA was prepared with longitudinal wires and snow cooling as was was TNT Casting 4 of the text). Comp B is RDX/TNT/Wax, 60/40/1; RDX, cyclotrimethylene trinitramine. Test results on Comp B first reported in Ref. (43).

b. Relationship $P_i = a + b\ d^{-1}$ assumed. See Ref. (43). P_i was derived from Hugoniots of PMMA (5), TNT (6) and Comp B (6). The TNT Hugoniot was also used for DINA.

c. Values obtained by extrapolating those at the two smaller diameters.

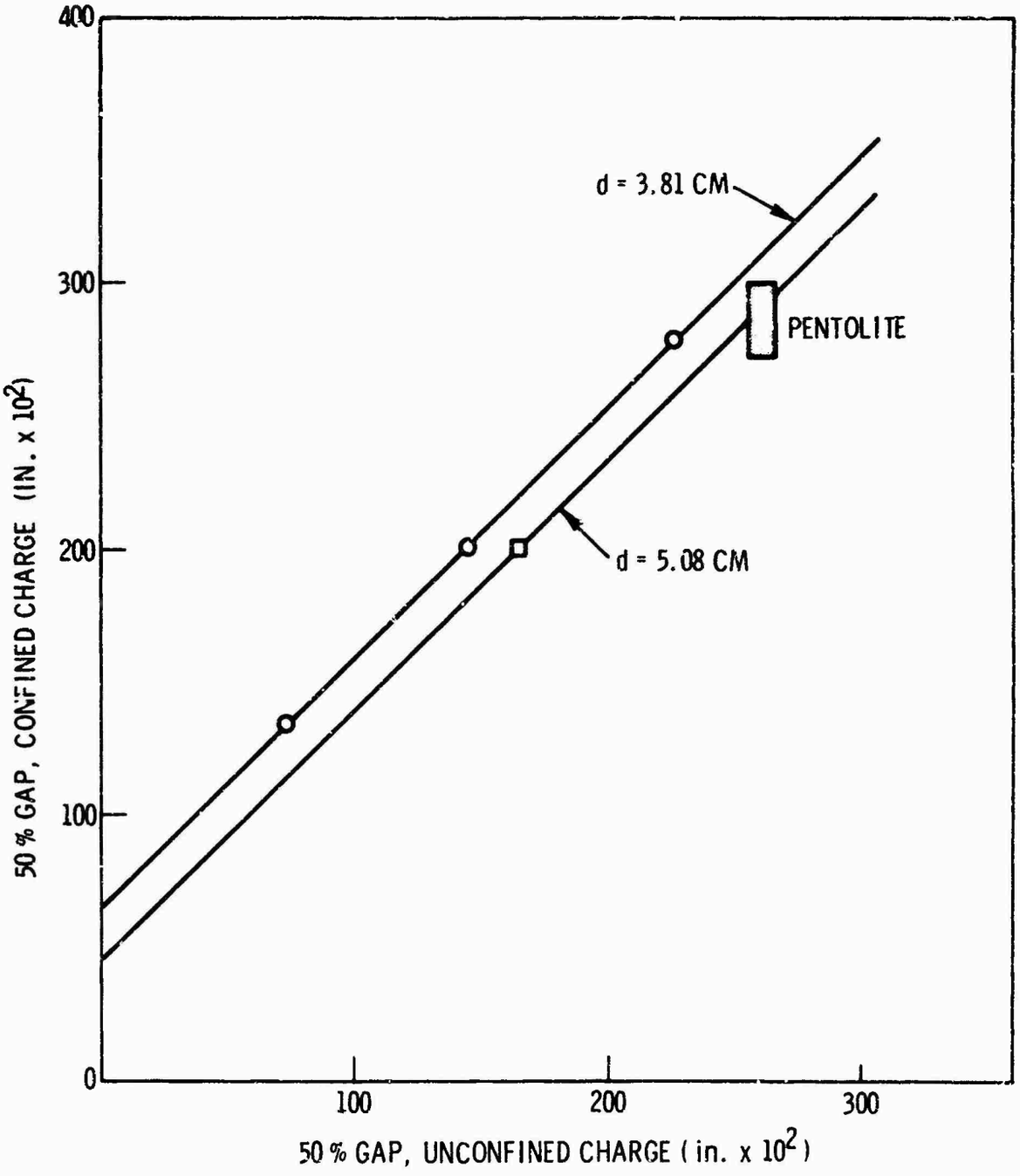

FIG. A1 EFFECT OF CONFINEMENT ON 50 % GAP IN LSGT

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13. ABSTRACT

(U) Shock sensitivity of an explosive includes its threshold for propagation of steady state detonation at the critical diameter (d_c) as well as its numerous thresholds for initiation of detonation under different transient conditions. Data for TNT charges of differing degrees of homogeneity are used to show a continuous variation of d_c with the initiating pressure P_i measured with the NOL large scale gap test. An example of a critical curve is constructed in the pressure-time plane; it runs from the threshold conditions at d_c through those at P_i. It is suggested that all other initiating pressures measured for the same charge would also fall on this curve which illustrates the relationship between the different threshold values.

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Detonability Critical diameter Shock sensitivity LSGT Values TNT						